Pergamon
0042-6989(95)00146-8
Vision Res., Vol. 36, No. 5, pp. 699–706, 1996

0042-6989/96 $15.00 + 0.00

Perceived Motion in Depth

ELI BRENNER*†, A. V. VAN DEN BERG*, W. J. VAN DAMME*

Received 12 December 1994; in revised form 24 March 1995; in final form 4 May 1995

We examine how various sources of information contribute to the percept of motion in depth. Subjects were presented with targets moving in depth, and were asked to judge their velocities and final positions. On each presentation, the target's position relative to the two eyes (target vergence), the size of the target's retinal image and the difference in this image's position relative to that of the background in the two eyes (relative disparity), each either changed as they normally would for a target moving at a fixed speed towards the observer, or did not change at all. Subjects' judgements for various such combinations show that all three sources of information influence both the perceived velocity of motion in depth and the final perceived position, but in different ways. This is not too surprising, because the assumptions that the use of each source of information are based on, are different for the two tasks. We propose that the way the different sources are combined is governed by the likelihood of the assumptions, that are required to use that information, being true under the given circumstances.

Velocity Position Looming Binocular vision Human

INTRODUCTION

When an object moves in depth, the size of its retinal image changes, and its retinal image shifts differently relative to images of surrounding structures in the two eyes. Such changes in retinal information can, and do, provide information on the object's motion in depth [we will discuss some of the evidence in the Discussion; for an extensive review see Regan, Kaufman and Lincoln (1986b)]. A possible advantage of not relying exclusively on a single source of information when judging an object's motion in depth, is that this could make us less susceptible to each source's limitations. However, to do so we must combine (conflicting) information from different sources in a meaningful manner. We appear to do so. For example, we do not duck when we watch someone inflate a balloon, despite the balloon's retinal image growing quite rapidly. In the present study we will examine how information from different sources is combined.

The most extensive previous study on this topic compared the relative effectiveness of two sources of information (Regan & Beverley, 1979). Regan and Beverley's experiments examined the rate of change in disparity that was required to cancel the perceived motion in depth due to a given change in target size. In their experiments, simultaneous changes in disparity and size, corresponding with motion in opposite directions, made the target appear to be stationary. They found that changing disparity becomes more effective when either velocity or inspection time is increased. A drawback of their way of comparing sources of information is that it does not allow one to differentiate between an increased effectiveness of one measure, and a decreased effectiveness of the other. This limits the search for logic in the rules governing the relative weights given to various sources of information. In the present study we therefore use a matching task instead.

We examine three sources of information: target vergence (the angle between the lines connecting the target with the nodal point of each eye), relative disparity (the difference between the target vergences of two structures) and retinal image size. We will concentrate on how changes in these sources of information are used, and deal with the question of how we derive target vergence from ocular vergence and retinal disparity, and how we extract the information on the object's motion in depth from the object's changing retinal image, in the Discussion.

When an object moves in depth, its perceived distance usually also changes (unless stated otherwise, the term *distance* will always refer to the distance from the observer). As the perceived distance is not necessarily based on the same information as the perceived motion, a discrepancy could arise, especially in experiments in which various sources of information simultaneously support different extents of object motion in depth. We will examine the possible interaction between the perceived velocity and the perceived displacement (i.e. change in perceived position) by determining both measures for each simulated motion in depth.

*Department of Physiology, Erasmus University, P.O. Box 1738, 3000 DR Rotterdam, The Netherlands.
†To whom all correspondence should be addressed [*Email* BRENNER @FYS1.FGG.EUR.NL].

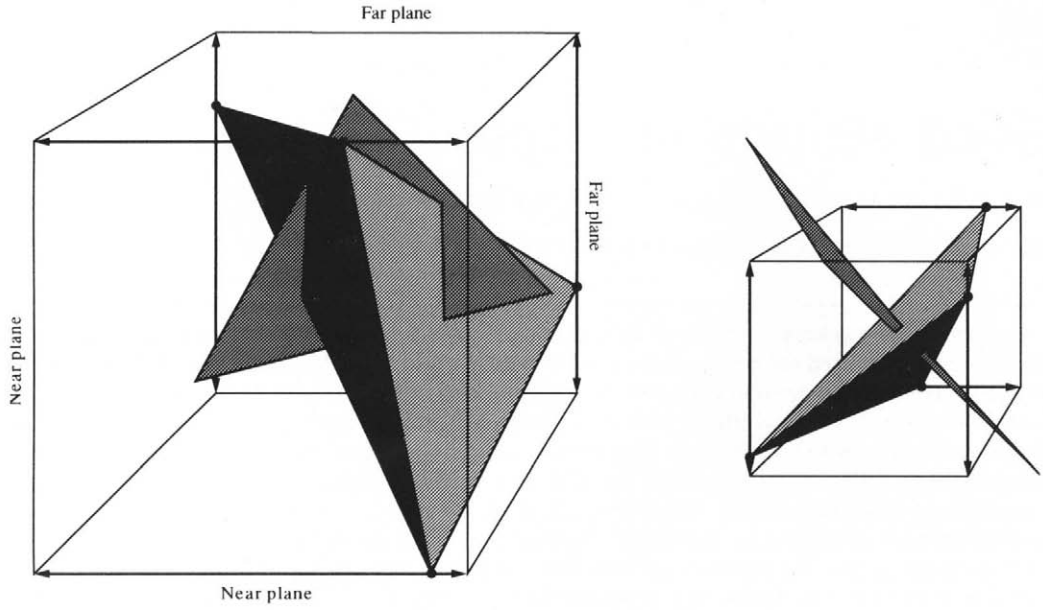

FIGURE 1. Two examples of the kind of targets used in our experiments. The shape of the target was changed whenever a setting had been made. Each target was built up of three triangles. Two of these triangles shared two corners, which were at random positions along opposite sides of the near plane of an imaginary cube (indicated by arrows). Each had its third corner at a random position on one of the orthogonal sides of the far plane. The third triangle was on a plane parallel to the cube's near plane and half-way between the near and far planes. This triangle's corners were at random positions within an area that was 4 times as large as the cube's planes, with the restriction that the triangle must intersect the other two triangles. The imaginary cube had sides of between 1.5 and 6 cm (determined at random). The matching target was a cube with sides of 3 cm. With target distance we always refer to the distance to the near plane.

We find that target vergence, relative disparity, and retinal image size contribute differently to the perceived velocity and to the perceived displacement. We discuss how this may be related to the advantages and disadvantages of each of the three sources of information.

METHODS

There were four experiments. In all four, selected sources of information specified that a target was approaching the observer, whereas the others specified that it was static. In two experiments we asked subjects to indicate the target's velocity. In the other two we asked them to indicate the position at which the target disappeared. For each task the difference between the two experiments was whether all sources provided similar information on the target's distance at the beginning or at the end of the presentation.

All the experiments were performed with simulated objects on a computer screen (Silicon Graphics GTX-210 computer and HL69SG monitor). The screen was 34 cm wide (1280 pixels) and 27 cm from top to bottom (492 pixels). Screen luminance was 13 cd/m^2 for light pixels and 0.02 cd/m^2 for dark ones. Perspective projection was used to display objects on this screen. Subjects sat with their head in a chin-rest at 60 cm from the screen. Images were presented at a rate of 120 Hz. LCD shutter spectacles ensured that alternate frames were presented to the left and right eyes. Each frame provided a new image; with the appropriate perspective for the eye for which it was intended (taking account of the separation between *individual* subjects' eyes) and the target at its simulated position at that moment. Red stimuli were used because the LCD shutter spectacles work best at long wavelengths (about 33% transmission when "open" and 0.3% when "shut"). The room was dark, so that subjects were unable to see anything except for the image on the screen.

The target that moved in depth was a complex shape built up of three triangles (see Fig. 1). It moved for 1 sec at a constant simulated velocity of 21.6 cm/sec towards the observer (either starting or stopping at a distance of 60 cm; the real distance to the screen). The target's size varied between trials. This variability, and the complexity of the target, was done to discourage subjects from judging the target's distance from assumptions on the simulated size.

The matching target was a cube with sides of 3 cm. When matching velocities, this cube moved from left to right at a velocity that was set by the subject (at a distance of 60 cm; reaching the centre of the screen half-way through the 1 sec presentation). When matching the position at which the target disappeared, it remained stationary at a distance that the subject could set (target vergence, size and relative disparity all changing in accordance with that distance).

The background (for both targets) consisted of 12 simulated triangles with sides of 12 cm. The triangles were not all at the same simulated distance, but were at (randomly chosen) distances between 80 and 100 cm (when the target moved from 60 to 38.4 cm away), or

between 100 and 120 cm (when the target moved from 81.6 to 60 cm away). The triangles were more or less randomly distributed within the boundaries of the screen. Their positions varied with each presentation.

When the target started at a distance of 60 cm, the *initial* information on the target's distance (target vergence, range of relative disparities and range of possible target image sizes) was the same for all conditions. The *final* target vergence and range of relative disparities were therefore highly correlated with the changes in these measures (this was less so for retinal target size, because the simulated target size was varied between trials). When the targets stopped at 60 cm, the converse was true. In the latter case there was no correlation between the final values and the changes during the presentations (note that the motion also took place at a larger simulated distance).

Perceived velocity

When making their settings, subjects were free to look at the target and matching motions as often as they pleased. There were no restrictions on eye movements. Subjects were presented with the target motion (in depth) if they pressed the left mouse button, and with the matching (lateral) motion if they pressed the right button. The velocity of the lateral motion was determined by the position of the mouse. When satisfied with the setting, the subject pressed the middle mouse button and the next condition was presented. There were eight conditions, each of which was presented five times to each subject, all in random order.

Perceived final position

Subjects were shown the target motion once, after which the matching cube appeared (at a random distance). The subject's task was to move the cube to the position at which the target disappeared. They were informed that we consider the simulated position of the near plane (see Fig. 1) to be the target's distance. The cube's simulated distance was determined by the position of the mouse. Matches were made for the same eight conditions, as well as for two additional conditions in which the targets were static (at distances of 60 and 38.4 cm). Each condition was presented 10 times to each subject, in random order.

The simulations of motion in depth (the eight conditions)

The first condition was a full simulation of a target moving towards the observer. The target images destined for the two eyes were shifted in opposite directions across the static background, changing target vergence and relative disparity by about 3.5 deg for targets that start 60 cm away, and by about 1.5 deg for targets that stop there. The size of the target's image increased by 56% for the nearer motion and 36% for the more distant motion. As we used three-dimensional targets, the difference in disparity between near and far parts of the target also changed during the presentation (by about 25 and 10 min arc), and the target's orientation relative to the line of sight changed in opposite directions in the two eyes. The changes in vertical disparity that should have occurred during the target's motion in depth were smaller than the vertical resolution of our display, and close to the resolution of the human eye. The required accommodation obviously also did not change when the target's distance changed, but accommodation is known to be a poor cue for judging distance (Collewijn & Erkelens, 1990; Sedgwick, 1986).

The second, third and fourth conditions consisted of selectively eliminating changes in target vergence, relative disparity and target image size. Selectively eliminating changes in target vergence maintains all changes in the image reaching each eye, but the eyes do not have to move to maintain fixation on the target. This is accomplished by rotating the whole simulated scene independently (in opposite directions) around the two eyes to compensate for the change in target vergence, before effecting the perspective projection on the screen. Selectively eliminating changes in relative disparity leaves all changes to the target's image intact. The background's image on the screen shifts together with the target so that the relative disparity between the target's near plane and the background does not change (i.e. background vergence—defined in analogy with target vergence—changes by the same amount as target vergence). Selectively eliminating changes in image size is accomplished by not changing the size of the target's image on the screen. The simulation corresponds with an approaching target which shrinks as it comes closer.

The fifth, sixth and seventh conditions consisted of isolated changes in target image size, relative disparity and target vergence. An isolated change in target image size is a simulation of a growing target (with its size increasing in accordance with the change in retinal image size during the full simulation). An isolated change in relative disparity is achieved by rotating the background in opposite directions around the eyes (decreasing background vergence by the angle with which target vergence would normally increase). Target vergence was changed on its own by rotating the initial scene independently (in opposite directions) around the two eyes, before effecting the perspective projection on the screen, so that the eyes had to be converged to maintain fixation but the image on each retina did not change.

The eighth condition was a simulation of motion of the background away from the observer. The change in relative disparity was identical to the change when the target moved towards the observer. To achieve this, we calculated (for each frame) how much each background element would have to move backwards to cause the same change in relative disparity as is caused by the approaching target in the full simulation. This motion of the background is then simulated. As a result, the stimulus is identical to that in the condition in which an isolated change in relative disparity is shown, except that the background "shrinks".

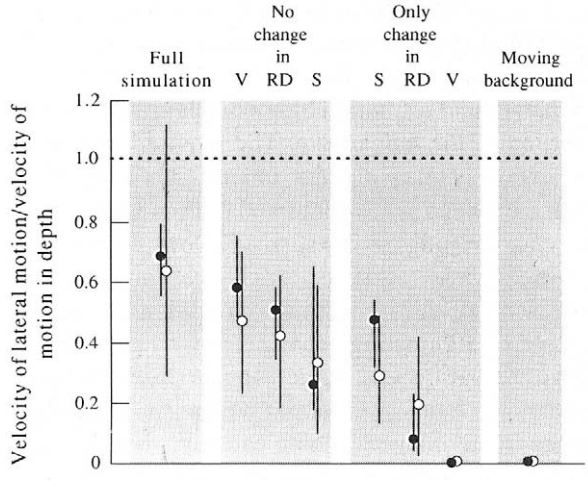

FIGURE 2. Median and intra-quartile range of seven subjects' average ratios between the set lateral velocity of the matching target and the target's simulated velocity of motion in depth (always 21.6 cm/sec), for each condition. V, target vergence; RD, relative disparity between target and background; S, target image size; ●, the *initial* image on the screen was always the same; ○, the *final* image on the screen was always the same; dotted line, perfect performance. Subjects always underestimated the motion in depth. Although changes in target vergence alone did not give rise to a percept of motion in depth, their absence did reduce the perceived velocity. Changes in relative disparity alone (by changing background vergence) resulted in some perceived target motion in depth, but this could be eliminated by making the background contract as if it were moving away. Changes in target image size contribute very strongly to the perceived motion in depth.

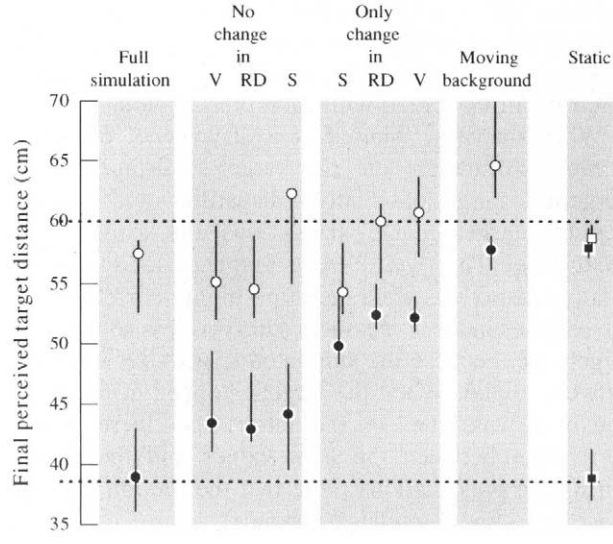

FIGURE 3. Median and intra-quartile range of the average positions at which the same seven subjects saw the targets disappear, for each condition. V, target vergence; RD, relative disparity between target and background; S, target image size; solid symbols, the *initial* image on the screen was always the same; open symbols, the *final* image on the screen was always the same; dotted lines, perfect performance. When the targets were static (at 38.4 or 60 cm; squares), subjects performed quite accurately. When the targets moved (circles), target vergence, relative disparity, and changing target image size contributed to about the same extent to the final perceived position. Note that the final target vergence and relative disparity always indicate a distance of 60 cm for the more distant motion (open symbols), whereas the final distance they indicate depends on how much they changed for the nearer motion (solid symbols).

Subjects

Apart from the first author, all subjects were colleagues who were aware of the questions being dealt with, but not of the specific stimuli. All had normal (corrected) acuity and intact binocular vision. The same seven subjects served as subjects in all four experiments (velocity and final position; motion starting or ending at 60 cm).

Analysis

Each subject's settings in each condition were averaged, and the median (symbols) and intra-quartile range (error bars) of the subjects' average settings are shown in Figs 2 and 3. As there were seven subjects, the median is the fourth largest value, and the top and bottom of the error bars show the second and sixth largest values. Although this gives a good picture of the variability between subjects for each condition, it somewhat masks the fact that individual subjects' responses changed systematically between conditions. As we are mainly interested in these systematic differences, and the variability between subjects is very large (see error bars), we used the Wilcoxon rank test to evaluate differences in performance between selected conditions (with $P<0.05$ indicating a significant difference). This statistical test compares the differences between individual subjects' settings under two conditions, so that it is not very sensitive to the overall variability between subjects.

RESULTS

Figs 2 and 3 show the median settings for the velocity and position matching experiments. The solid symbols are for the experiments in which the target started 60 cm away. The open symbols are for the experiments in which the target stopped 60 cm away. The conditions have been grouped into four categories. From left to right these are: the full simulation of an approaching target; simulations in which one of the sources of information on motion in depth indicates that the target is static (while the others suggest that the target is approaching); simulations in which only one source of information indicates that the target is moving in depth; a simulation of a receding background. In Fig. 3 there is an additional category that consists of simulated static targets at distances of 38.4 and 60 cm.

Perceived velocity

Fig. 2 shows the velocity of lateral motion that was set to match the reference motion in depth, as a fraction of the latter (always 21.6 cm/sec). The set lateral velocity (of the cube at 60 cm distance) was very similar for targets moving from 81.6 to 60 cm (○) and ones moving from 60 to 38.4 cm (●). The differences were never statistically significant, but the variability between subjects was larger for the more distant motion. The full simulation condition was an as good as possible simulation of motion in depth. Nevertheless, subjects

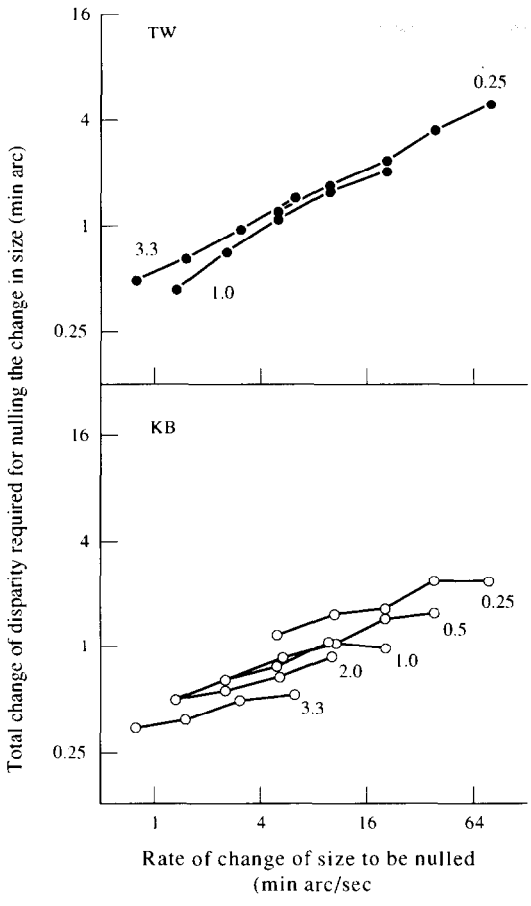

FIGURE 4. Change in disparity (or target vergence) that is required to cancel the opposing percept of motion in depth caused by changing target size. Data for two subjects, replotted from Fig. 5 of Regan and Beverley (1979) to show that the *total* change in disparity may be crucial, rather than the *rate* of change in disparity (using the total change in size, as well, shifts the lines for different durations apart again). The numbers beside the lines give the duration of the motion in sec.

set a considerably lower lateral velocity than the simulated velocity of motion in depth.

When the image on the retina changed in the same manner as during the full simulation, but vergence did not change, subjects set a slightly lower velocity of lateral motion (than for the full simulation). This was statistically significant for the more distant motion (○), and just failed to reach statistical significance for the closer motion (P=0.06; ●). Similarly, when changes in relative disparity were selectively omitted from the simulation, subjects set a lower lateral velocity (P<0.05 in both cases). The reduction in perceived velocity was even more evident when retinal target size did not change, although the effect failed to reach statistical significance for the nearer motion (P=0.06). Thus all three sources of information influence the perceived motion in depth.

When a single source of information suggested that the target was approaching, the perceived velocity was always significantly reduced. Changing target image size gave rise to the largest perceived velocity, while changing target vergence did not result in any perceived motion in depth. When a moving background was simulated, the change in relative disparity was identical to that when relative disparity changed in isolation. The only difference was that the triangles forming the background contracted as their disparity changed, so that the image became a complete simulation of a moving background, with no conflict between cues. In this case there was no perceived target motion in depth. Thus, the influence of changing disparity can be modulated by information that is not directly related to the target's motion (changing size in the background).

Perceived final position

Figure 3 shows the distances at which the cube was set to match the final positions of the moving targets (circles). These distances were compared with the distances subjects set for static targets at 60 and 38.4 cm (squares). The static target at 60 cm was consistently judged to be slightly nearer than 60 cm. The other static target was correctly judged to be close to the simulated distance of 38.4 cm (lower dotted line).

For the motion from 60 to 38.4 cm (the nearer motion; solid symbols), the initial image of all the moving targets was equivalent to that of a static target at 60 cm. For the full simulation, the target's final position was correctly judged to be about 38.4 cm away. In all other cases, the target's final position was judged to be more distant (although this was not statistically significant for the simulations in which changes in vergence and relative disparity were selectively omitted). Changing target image size, target vergence and relative disparity contributed to similar extents to the perceived position, and their influences appeared to be more or less independent (each accounted for about one-third of the change in position). The final perceived position of "moving" targets was always significantly nearer than that of static targets at 60 cm, except for when changing relative disparity was accompanied by changes in the size of the image of the background (moving background).

For the motion from 81.6 to 60 cm (the more distant motion; open symbols), the final image was always the same, corresponding with a static target at 60 cm, so that any differences in final perceived distance must be due to the preceding motion. The open symbols in Fig. 4 suggest that the target is seen to disappear at a smaller distance when target image size increases (first three and fifth condition from the left), than when it does not (other four conditions). Only when target image size changed on its own, however, was the final perceived target distance *significantly* smaller than that for the static targets (for the moving background it was significantly larger).

DISCUSSION

A comparison of the perceived positions for the nearer motion (solid symbols in Fig. 3), and of the corresponding perceived velocities (in Fig. 2), shows that the perceived motion need not be consistent with the perceived change in position. The two clearly rely to different extents on the three sources of information. For instance, changes in target vergence alone did not make

the target appear to move, but its final perceived position was nearer than it would have been if target vergence too had not changed (the static target at 60 cm). Similarly, changing image size determined the perceived motion in depth to a much larger degree than it did the perceived change in position. We must therefore keep the arising conflict between these two percepts in mind when interpreting the role of the individual sources of information within each one. Moreover, as we are looking for logic in the rules governing the weight given to the various sources of information, we will consider the merits and limitations of each of the sources of information on motion in depth.

THE PERCEIVED DISTANCE

Theoretically, target vergence is a reliable measure of distance. However, the ability to derive target vergence from retinal disparity and extra-retinal information on the orientation of the eyes appears to be quite limited (Gogel, 1982; Sedgwick, 1986; Collewijn & Erkelens, 1990; Johnston, 1991). That is presumably why our subjects also used other measures of distance. Although relative disparity is generally considered to be a measure of *relative* distance, it can provide reliable information on *absolute* distance if the reference is either far away (in which case relative disparity is equivalent to target vergence), or if its distance is known. As we used a matching task in this study, subjects did not even have to know the reference's distance. It would be enough for them to assume that the background was at the same distance during the target's motion in depth, as when adjusting the cube's distance. Apparently our subjects made this assumption.

The finding that the changing image size influences the perceived final position is somewhat more surprising. For the nearer motion it is conceivable that subjects were influenced by the larger *average* final image size (although this should have been masked by the large, random variations in the initial simulated target size). However, for the more distant motion the (average) measures in the final images were always the same. It is therefore evident from the open symbols in Fig. 3 that the *change* in target image size made the targets appear to be nearer. This influence of changing size cannot be an extrapolation of the target's perceived motion, or of ocular convergence: when only target image size changed (fifth condition from the left), neither the perceived velocity (Fig. 2) nor vergence eye movements (Erkelens & Regan, 1986) were larger than when changing image size was selectively eliminated (fourth condition from the left).

Thus, even when image size itself does not provide information on distance, changing image size influences the perceived distance. This influence of changing size on the perceived position provides an alternative explanation for the findings of Regan and Beverley (1979) that were mentioned in the Introduction (which we will now present to illustrate how the perceived position and perceived motion *could* interact).

Regan and Beverley asked subjects to cancel fixed rates of change of target size with changes in target vergence (presented as changes in retinal and relative disparity, with subjects fixating a stationary point). They found that changing disparity becomes more effective when either velocity or inspection time is increased. The influence of inspection time is surprising, because it implies that a target that appears to be stationary when certain rates of change of size and disparity are presented, will appear to move when the duration of the presentation is increased or decreased. Conversely, even with optimal cancellation, targets should appear to move during the initial part of a long presentation. We propose that what subjects were actually doing was cancelling the total perceived displacement. Thus, they were cancelling the decrease in perceived distance due to the increasing image size, by manipulating target vergence. Replotting the data from Regan and Beverley's (1979) Fig. 5, using the *total* change in disparity rather than the *rate* of change in disparity, supports this proposal (see Fig. 4): the required total change in disparity only appears to depend on the rate of change in size. If our interpretation is correct, Fig. 4 implies that the influence of changing size on the perceived position depends on the rate of change in size, but not on the duration of the presentation. For our *position* task, this means that changing the duration of presentation will alter the relative contributions of changing image size, target vergence and relative disparity. Whether this is so was not examined in the present study, in which the presentation time was always 1 sec.

THE PERCEIVED VELOCITY

Motion in depth was systematically underestimated relative to lateral motion. We have no explanation for this finding. It may be related to the recently reported systematic distortion in our spatial representation (Todd, Tittle & Norman, 1995).

Changing retinal image size

In our experiments the target's perceived velocity mainly depended on its changing image size (Fig. 2). When an object approaches us, its retinal image expands. For a ball, the relative rate of change in angular size (the rate of change in the image's angular extent divided by the current angular extent; in one dimension) is equal to (minus) the relative rate of change in distance (the rate of change in distance divided by the distance), so that the changing retinal image size is indicative of the ball's motion in depth. One limitation of using changes in retinal image size to judge motion in depth, is that retinal image size also increases when an object actually grows. However, fast changes in an object's dimensions do not occur very frequently in everyday life. For objects other than balls, retinal image size can also change as a consequence of changes in surfaces' orientations relative to the line of sight. For most three-dimensional objects, decreases in the size of the retinal image of one surface, due to changes in its orientation, will roughly be

compensated for by increases in the size of retinal images of other surfaces. Moreover, changes in orientation could be recognized as such on the basis of local deformations in the surfaces' images (Koenderink, 1986). There is ample evidence that changing size usually does lead to a percept of motion in depth (Regan & Beverley, 1978, 1979, 1983; Regan *et al.*, 1986b; Swanston & Gogel, 1986; Heuer, 1987).

Changing retinal image size provides an estimate of an object's velocity in terms of its distance. Thus information on distance can be expected to influence the way in which information from changing size and from the change in position are combined. Indeed, if the relative rate of change in image size alone had determined the perceived velocity, the perceived velocity for the full simulation of the more distant motion (open symbols) would have been about three-quarters of that for the nearer motion (solid symbols); as it was when only the image size changed. In the latter case, the rate at which the image size changed was the only difference between the two presentations. In the full simulations, the perceived velocity at the two distances was quite similar. Thus, the changing image size was indeed combined with binocular information on the target's distance.

Does this mean that target vergence and relative disparity are only used to scale the changing image size with the distance? Clearly not, because when changes in target vergence and relative disparity were eliminated (from simulations of the nearer motion), the perceived distance became larger, but this did not result in faster perceived motion. Moreover, subjects saw motion in depth without changes in target image size in some conditions.

Changing target vergence and related measures

How could we obtain information on a target's motion in depth from the changing target vergence? If we would not move our eyes, changes in target vergence would result in corresponding changes in retinal disparity. Normally, however, ocular vergence at least partly compensates for changes in target vergence (Erkelens & Collewijn, 1985b; Erkelens & Regan, 1986), so that changes in retinal disparity and extra-retinal information on the rate of ocular convergence would have to be combined to obtain the change in target vergence. Our ability to do so appears to be quite limited. Isolated targets that don't change size when their vergence changes, are usually not seen to move in depth (Erkelens & Collewijn, 1985a; Regan, Erkelens & Collewijn, 1986a; this study). Some motion in depth is perceived if the target is very small (so that the conflict with changing size is less evident), but this could be induced by the change in perceived position. Similarly, the slightly lower set velocity when vergence did not change in accordance with the other sources of information in the present study (second condition from the left in Fig. 2), could be due to the smaller perceived displacement.

One could use changes in relative disparity to estimate how much target vergence has changed. Under the assumption that the background [or the most distant structure (Brenner, 1991; Mershon, Jones & Taylor, 1993)] is static, the change in disparity relative to the background could provide a purely retinal estimate of the change in target vergence (because relative disparity is the difference between target vergence and background vergence, and background vergence does not change). A consequence is that motion of the background should be attributed to the target; as indeed it sometimes is (Erkelens & Collewijn, 1985a; Mershon *et al.*, 1993).

The sensitivity for perceiving motion in depth from changes in target vergence increases dramatically when a stationary reference is displayed [i.e. when there is also a change in relative disparity (Regan *et al.*, 1986a)]. In the present study, for the more distant motion, the relative disparity changed from about 1.2 to about 2.8 deg. For the nearer motion, it changed from about 2 to about 5.4 deg. When these changes in relative disparity were presented on their own (Fig. 2; sixth condition from the left), the smaller change at the smaller relative disparity (○) gave rise to a higher velocity of perceived motion in depth than the larger change at the larger disparity (●; note that target vergence was the same in both conditions). This may be because subjects assumed that the *background* was at the same distance in both cases, so that a larger disparity implies a nearer target, and therefore slower motion (the change in relative disparity provides an estimate of an object's velocity in terms of its distance). Alternatively, we may simply be able to detect smaller differences in disparity when the disparity is small, and therefore rely more on changing disparities under such conditions.

When changes in relative disparity were presented on their own, subjects saw an approaching, shrinking target. The extent to which a change in relative disparity is attributed to target motion (and shrinking) depends on other aspects of the display. When relative disparity changed as a result of changing target vergence (i.e. when both vergence and relative disparity changed: fourth condition from the left in Fig. 2), the perceived velocity was significantly higher ($P<0.05$ in both experiments) than when only relative disparity changed (sixth condition). Changing the size of background elements so that the presentation was a simulation of a moving background (the same change in relative disparity was presented, but the background also shrunk: rightmost condition) eliminated the perceived target motion altogether.

Handling conflicting information

We propose that subjects try to interpret the simulation in a manner that gives the least conflict between the different sources of information. It may seem that this cannot be so, because subjects interpreted a realistic simulation of a growing target (an isolated change in target size) as a change in target distance. However, assumptions about the environment can also be considered as a source of information. We have shown that subjects are willing to make assumptions concerning the

background's distance in order to be able to use information from relative disparity. Similarly, they must make the assumption that objects' sizes do not change in order to use changing image size as a measure of motion in depth.

Our study provides a clear example of how the weight attributed to a source can be influenced by a factor that is not directly involved in the motion itself: in the simulations of a receding background, changes in relative disparity were not interpreted as target motion, presumably because the required assumption of a static background was rejected. This shows that changes in the weights attributed to the different sources of information can help to limit perceptual errors. However, this subjective component may also be responsible for the large differences between subjects. Such differences limit the merit of quantitative studies on the interactions between conflicting sources of information, because the weight attributed to each source will depend on factors that are difficult to control in experiments.

REFERENCES

Brenner, E. (1991). Judging object motion during smooth pursuit eye movements: The role of optic flow. *Vision Research*, *31*, 1893–1902.

Collewijn, H. & Erkelens, C. J. (1990). Binocular eye movements and the perception of depth. In *Reviews of Oculomotor Research*, *4*, 213–261.

Erkelens, C. J. & Collewijn, H. (1985a). Motion perception during dichoptic viewing of moving random-dot stereograms. *Vision Research*, *25*, 583–588.

Erkelens, C. J. & Collewijn, H. (1985b). Eye movements and stereopsis during dichoptic viewing of moving random-dot stereograms. *Vision Research*, *25*, 1689–1700.

Erkelens, C. J. & Regan D. (1986). Human ocular vergence movements induced by changing size and disparity. *Journal of Physiology*, *379*, 145–169.

Gogel, W. C. (1982). Analysis of the perception of motion concomitant with a lateral motion of the head. *Perception & Psychophysics*, *32*, 241–250.

Heuer, H. (1987). Apparent motion in depth resulting from changing size and changing vergence. *Perception*, *16*, 337–350.

Johnston, E. B. (1991). Systematic distortions of shape from stereopsis. *Vision Research*, *31*, 1351–1360.

Koenderink, J. J. (1986). Optic flow. *Vision Research*, *26*, 161–180.

Mershon, D. H., Jones, T. A. & Taylor, M. E. (1993). Organizational factors and the perception of motion in depth. *Perception & Psychophysics*, *54*, 240–249.

Regan, D. & Beverley, K. I. (1978). Looming detectors in the human visual pathway. *Vision Research*, *18*, 415–421.

Regan, D. & Beverley, K. I. (1979). Binocular and monocular stimuli for motion in depth: changing-disparity and changing-size feed the same motion-in-depth stage. *Vision Research*, *19*, 1331–1342.

Regan, D. & Beverley, K. I. (1983). Visual fields for frontal plane motion and for changing size. *Vision Research*, *23*, 673–676.

Regan, D., Erkelens, C. J. & Collewijn, H. (1986a). Necessary conditions for the perception of motion in depth. *Investigative Ophthalmology & Visual Science*, *27*, 584–597.

Regan, D. M., Kaufman, L. & Lincoln, J. (1986b). Motion in depth and visual acceleration. In Boff, K. R., Kaufman, L. & Thomas, J. P. (Eds), *Handbook of perception and human performance 1, sensory processes and perception* (Chap. 19, pp. 1–46). New York: Wiley–Interscience.

Sedgwick, H. A. (1986). Space perception. In Boff, K. R., Kaufman, L. & Thomas, J. P. (Eds), *Handbook of perception and human performance 1, sensory processes and perception* (Chap. 21, pp. 1–57). New York: Wiley–Interscience.

Swanston, M. T. & Gogel, W. C. (1986). Perceived size and motion in depth from optical expansion. *Perception & Psychophysics*, *39*, 309–326.

Todd, J. T., Tittle, J. S. & Norman, J. F. (1995). Distortions of 3-dimensional space in the perceptual analysis of motion and stereo. *Perception*. *24*, 75–86.